NASA-CR-203020

AIAA 94-3104

HYDRAULIC CHARACTERIZATION OF FORMED PLATELET COMBUSTION CHAMBER LINERS

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AIAA/ASME/SAE/ASEE
30TH JOINT PROPULSION
CONFERENCE AND EXHIBIT
JUNE 27-29, 1994 / INDIANAPOLIS, INDIANA

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by

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PRA-SA-MSFC 27 OCT 1993 (ABSTRACT)

ABSTRACT

Many fabrication and design options exist to cool the main combustion chamber of a liquid fueled rocket engine. A milled slot, regeneratively cooled liner is the current state of the art, as demonstrated by its use on the Space Shuttle Main Engine. A prominent candidate to be the next advancement in combustion chamber liner fabrication and design is formed platelet technology.

As with any regeneratively cooled liner, the hydraulic behavior of the coolant as it flows through the platelet liner coolant passages must be known. Empirically based hydraulic predictive techniques have been developed for coolant flow Reynolds numbers (based on hydraulic diameter) up to approximately 10^6. These hydraulic predictive capabilities have been verified to within -5.4% to +4.3% of gaseous cold flow and cryogenic cooled hot fire test data obtained during the Advanced Main Combustion Chamber (AMCC) and Subscale Formed Platelet Chamber Liner programs, respectively.

INTRODUCTION

During the past two decades, NASA and the commercial rocket industry have been searching for a low cost, highly repeatable fabrication technique capable of providing a high performance cooling system for the main combustion chamber of a liquid fueled rocket engine. Many design and fabrication concepts have been proposed and attempted during this period. Reference 1 provides a good review of some of these concepts. As stated in Ref. (1) one of the more promising fabrication techniques is formed platelet technology. Formed platelet technology is a leading candidate for the cooling system of a main combustion chamber for three important reasons. These reasons, as highlighted in Reference 2, are a cost savings of approximately 80%, a reduction in fabrication time of approximately 75%, and an increased cycle life over the fabrication techniques used on the milled slot liner of the current Space Shuttle Main Engine (SSME).

The fabrication techniques used in formed platelet technology are the result of approximately three decades of platelet experience at Aerojet Propulsion Systems Plant. Reference 3 provides a brief history of the use of platelet technology in thermal management devices, while Reference 4 documents the fabrication flow plan of the Subscale Chamber (40000 lb thrust) Formed Platelet Liner. The use of platelets, instead of conventional fabrication techniques, provides the capability of a thin hot gas wall of precisely controlled thickness, cooling channels with high aspect ratios, and continuous variation of the coolant channel width. These fabrication capabilities result in a high performance cooling system, which can be optimized to use the available coolant pressure head in regions of highest return (i.e. regions of high local heat fluxes).

As with any fluid transfer system it is necessary to understand the hydraulics, or pressure loss, of the coolant as it flows through the cooling passages of the platelet main combustion chamber (MCC) cooling liner. The objective of this document is to demonstrate that the current platelet passage hydraulic predictive capabilities at Aerojet Propulsion Systems Plant are sufficiently accurate to design a formed platelet liner. To demonstrate these prediction capabilities test data obtained during two formed platelet liner programs will be presented. The Subscale Formed Platelet Liner program was initiated to prove that formed platelet technology could be used to fabricate a combustion chamber liner for a liquid fueled rocket engine. Following the success of the Subscale Chamber Formed Platelet Liner program, the AMCC program was initiated. The AMCC program fabricated a main combustion chamber for hot fire testing on the Space Shuttle Main Engine Technology Test Bed. The AMCC is composed of a single piece cast structural jacket, developed by NASA, and an Aerojet developed and fabricated formed platelet liner.

FABRICATION of PLATELET LINERS

Flow passages fabricated using platelet technology go through a three step process. First, individual material sheets, or platelets, are chemically etched to produce flow passages, see Figure 1. These platelets are then stacked and diffusion bonded to form a flat monolithic structure. These flat monolithic structures are then formed, see Figure 2, to the desired three-dimensional curvilinear contour.

Land-to-land ties, see Figure 3, are incorporated into the individual platelets to provide robustness during fabrication. During operation the land-to-land ties act as minor flow blockages in the flow passage and therefore result in flow pressure loss.

Quantifying the pressure loss associated with the land-to-land ties along with determining the frictional loss characteristics of platelet coolant passages were part of the current work.

ANALYSIS METHODOLOGY

Many sources, see for example References (5, 6, and 7), provide methodologies for predicting the coolant pressure loss through the coolant passages of a combustion chamber liner. These methodologies are based on a control volume analysis of a finite stream wise distance along the coolant passage. Figure 4 illustrates the control volume and the associated pressure loss expression. As shown, the flow pressure loss is a function of wall frictional loss characteristics (i.e. effective surface roughness) and passage geometry (i.e. changes in flow momentum).

The hydraulic analysis of a coolant passage fabricated using platelet technology must include the effect of the land-to-land ties. Figure 5 illustrates a control volume of a platelet passage and the associated pressure loss expression. As shown, it is necessary that the land-to-land tie drag characteristics, the passage frictional loss characteristics, and the passage geometric effects all be quantified prior to making pressure loss predictions for flows through platelet passages.

The minor pressure loss attributed to land-to-land ties are due to two loss mechanisms, namely, skin friction and pressure drag. It is anticipated that the loss characteristics of the land-to-land tie, with its almost rectangular cross section, would be between those of a flat plate and cylinder, see Figure 6 of Ref. (8), which represent the extremes of having only skin friction and pressure drag, respectively.

The land-to-land tie drag characteristics are also affected by three dimensional flow effects at the junction of the land-to-land tie with the end-walls (or lands) and the presence of the top and bottom surfaces of the coolant passage. The land-to-land tie to end wall junctions produce horse shoe vortices, see for example Ref. (9, 11, 12, 13, and 14). The horse shoe vortices, see Figure 7, increase the effective blockage of the flow obstruction and therefore the associated pressure loss relative to that of a two dimensional flow obstruction of the same cross section geometry. Also, following Refs. (8 and 15), the affect of the top and bottom surfaces of the passage on the tie drag coefficient is dependent upon the relative geometries of the flow obstruction and the flow passage. Therefore, the presence of the top and bottom walls of the passage may act to increase or decrease the tie drag coefficient.

Due to the complexity of the flow field within a platelet passage it was deemed impractical to analytically predict the coolant pressure loss. Therefore, a rigorous test program was initiated to develop an empirical correlation to aid in predicting flow pressure loss through platelet passages.

TEST HARDWARE

Four pieces of test hardware have been used to establish and verify the current platelet passage hydraulic predictive model. These four pieces of hardware include:

(1) two hydraulic characterization panels,
(2) the Advanced Main Combustion Chamber cooling liner, and
(3) the Subscale Chamber Formed Platelet liner.

The two hydraulic characterization panels, see Figure 8(a), were designed, fabricated, and tested as part of the AMCC program. The objective of these panels were to isolate and quantify the hydraulic loss mechanisms (i.e. friction, curvature, and land-to-land ties) of platelet coolant passages. To realize this objective the panels were designed with 36 different passage designs, each passage design being fabricated at least twice to investigate fabrication repeatability. The passages were designed and fabricated to include a wide range of channel and land-to-land tie geometry. In addition, the panels were designed and fabricated such that the flow static pressure could be measured in two locations along the passage. Figure 8(b) illustrates the two static pressure ports installed in each passage within the Hydraulic Characterization Panels. These pressure ports provided the pressure loss measurement over the "test section" of each flow passage.

The coolant passages of the AMCC liner were designed to cool the hot gas wall of the liner while meeting the Large Throat SSME MCC liner coolant pressure loss requirement. Figure 2 illustrates an AMCC liner panel in the flat and formed configurations. The AMCC coolant passage design includes a channel width range of 0.020 to 0.042 inches and a channel aspect ratio range of 4.1 to 10.4. This passage design was tested in both the flat and formed configuration. These data were used to verify the hydraulic predictive methodology, outlined in the Analysis Methodology Section, and demonstrate that the coolant passages within the AMCC liner met the pressure loss requirement of the Large Throat SSME.

The Subscale Chamber (40000 lbf thrust) Formed Platelet liner was designed and fabricated by Aerojet for hot fire testing by NASA at Marshall Space Flight Center (MSFC). The objective of this program was to demonstrate formed platelet liner technology as applied to cooling liners of liquid fueled rocket engines. Figure 9(a) illustrates the chamber prior to installation on the test stand while Figure 9(b) is a photograph of a hot fire test of the Subscale Chamber Formed Platelet Liner. The Subscale Chamber liner coolant passage design, see Figure 10, includes a channel width range of 0.020 to 0.034 inches and a channel aspect ratio range of 5.0 to 9.0. The hot fire tests of the cryogenic hydrogen cooled platelet liner provided test data to verify the thermal/hydraulic predictive models as applied to actual "flight-like" conditions. These "flight-like" conditions include the use of a cryogenic cooling fluid and non-uniform and non-symmetrical heating of the flow/coolant passage.

TEST SETUP, INSTRUMENTATION and TEST SEQUENCE

The test setup, instrumentation and test sequence for each piece of tested hardware will be discussed herein.

Hydraulic Characterization Panels Test Setup, Instrumentation and Test Sequence

Figure 11 illustrates the hydraulic characterization panel test setup. As shown, the gas supply was maintained constant using a pressure regulator. The gaseous flowrate was measured using a calibrated sonic venturi. Each pressure measurement was made using redundant pressure transducers. To improve the accuracy of the pressure measurement the pressure transducers were gauge range optimized. This resulted in a pressure measurement uncertainty of $\pm 0.26\%$ of the full scale range of the pressure transducer. This pressure transducer setup resulted in an estimated uncertainty, see for example Ref. (16), of the flow pressure loss through the passage of $\pm 0.9\%$ to $\pm 5.6\%$ of the measured pressure loss. The flow temperature was measured using Chromel-Alumel thermocouples prior to the sonic venturi and in the supply and discharge tooling of the characterization panel. A back pressure orifice was installed just upstream of the flow discharge to atmosphere to ensure that the flow through the platelet passage was maintained below a Mach number of 0.3.

The test sequence for the hydraulic characterization panels was initiated with a pre-test, high pressure static leak test. During the static leak test the discharge valve was closed, the supply pressure was set to approximately 1500 psig, the supply valve was closed, and the pressure in the hydraulic panel was monitored for one minute to detect system leaks. Following confirmation that the system did not leak the flow tests were performed. A flow test consisted of setting a supply pressure, monitoring the pressure until it was stable, taking multiple (approximately 50) pressure and temperature measurements over a time period of approximately 1 second, the next flow setting was then established and test data taken. Following the flow tests a post-test high pressure static leak test was performed. The post-test leak test was performed in the identical manner as the pre-test static leak test. If the post-test static leak test indicated no system leaks the test was deemed completed and the next test was initiated.

AMCC Liner Panels Test Setup, Instrumentation and Test Sequence

Figure 12 presents the schematic of the test setup for the AMCC Platelet Panels in both the flat and formed configurations. The gaseous supply pressure was maintained constant using a pressure regulator. The static pressure was measured in the coolant supply and discharge tooling with redundant pressure transducers. The flow was discharged through a calibrated sonic venturi to the atmosphere. The sonic venturi inlet pressure was measured using redundant pressure transducers while the venturi downstream pressure was measured by a single pressure transducer. The use of redundant transducers resulted in a pressure measurement uncertainty of ±0.26% of the full scale range of the transducers. These measurement uncertainties resulted in an uncertainty of the measured flow pressure loss of ±7.9 or ±15.7 psi (or ±1.8 to ±3.15% of the measured pressure loss), depending on the pressure transducer setup in place. The gas flow temperature was measured using Chromel-Alumel thermocouples.

The test sequence for the AMCC panel tests was similar to that of the hydraulic characterization panels. A pre-test high pressure static leak test was performed. During the static leak test the pressure in the AMCC panel was monitored for one minute to detect system leaks. Following confirmation that the system did not leak, the flow test was performed. The flow test consisted of setting a supply pressure, monitoring the pressures until they were stable, taking multiple pressure and temperature measurements over approximately 1 second, and then setting the next supply pressure and repeating the above sequence. Once each flowrate of interest was tested the supply pressure was removed.

Subscale Formed Platelet Liner Test Setup, Instrumentation and Test Sequence

Hot fire testing of the Subscale Chamber Formed Platelet Liner was performed at NASA Marshall Space Flight Center Test Position 116. Figure 13, obtained from Ref. (2), illustrates the test stand and the instrumentation setup. The pressure transducers used had a measurement uncertainty of ±12 psi for a 5000 psig full scale reading, see Ref. (17). This measurement uncertainty results in an uncertainty of the measured coolant pressure loss of approximately ±14.7 psi. The coolant inlet and exit temperatures were measured using redundant measurement instrumentation. The flow temperature was measured using a Chromel-Constantan thermocouple along with a Resistance Temperature Detector (RTD). The test sequence is provided in detail in Reference (2).

The hot fire test data presented represents the data obtained as of December, 1993. The ongoing testing consists of two phases, the first phase tests were conducted with a nominal coolant flowrate of approximately 11.4 lbm/sec while the second phase of tests had a nominal coolant flowrate of approximately 8.5 lbm/sec. The first phase of testing was completed in December, 1993, while the second phase was initiated in January, 1994.

TEST DATA

Three sets of test data are presented here. The first set of data, that obtained from the hydraulic characterization panels, represent the basis of the hydraulic model developed. Meanwhile, the gaseous cold flow data and cryogenic hydrogen cooled hot fire data of the AMCC and Subscale Chambers respectively, provide the validation of the thermal/hydraulic model.

Hydraulic Characterization Panel Testing

Test data obtained from the hydraulic characterization panels defined the frictional loss characteristics of both straight and curved passages and the drag characteristics of land-to-land ties. During the gaseous Nitrogen and Hydrogen cold flow tests of the Hydraulic Characterization Panels 280 tests were conducted covering a Reynolds number (based on hydraulic diameter) range of $2(10^5)$ to $1.2(10^6)$. Each test providing a defining data point. The test data presented represents a small fraction of the data obtained during the test program and are presented to illustrate data consistency.

Figure 14 presents land-to-land tie drag coefficient data obtained during the testing of the hydraulic characterization panels. These data demonstrate the repeatability of the land-to-land tie drag coefficient as the test fluid (either ambient nitrogen or hydrogen gas) was changed. In addition, the consistency of the data obtained from two "identical" passages illustrates the repeatability of the platelet etching manufacturing process. The uncertainty of the flow pressure measurements resulted in uncertainties of ± 1 to $\pm 6\%$ in the land-to-land tie drag coefficient. Comparison of the land-to-land tie drag coefficients to drag coefficients from the literature were favorable. Therefore, test data obtained as part of the current programs are consistent with previously published results.

These test data, see Figure 14, in conjunction with the remaining gaseous cold flow test data, are the basis of the hydraulic predictions for both the AMCC and Subscale Chamber Formed Platelet Liners.

AMCC Platelet Panel Testing

The gaseous Nitrogen cold flow test data obtained, up to this point in time (February, 1994), from the AMCC platelet panels covered a Reynolds number (based on hydraulic diameter) range of $1.0(10^5)$ to $6.5(10^5)$. The 140 cold flow data points, were obtained while the panels were in both the flat and formed (i.e. converging-diverging nozzle contour) configurations, see Figure 2. The objective of these tests were to demonstrate the hydraulic characteristics of the cooling passage design over a wide range of Reynolds number prior to use in a hot fireable assembly.

Figure 15 presents the measured and predicted AMCC flat panel gaseous Nitrogen flow pressure drop as a function of gas flowrate. The measured pressure loss data represents the average of approximately 50 measurements taken for each flow condition over a time span of approximately 1 second. The uncertainty bands for each data point is the estimated measurement uncertainty for each test setup. As this figure illustrates the predicted pressure loss approximates the best fit least squares curve fit of the measured data to within -2.3% to +4.3%.

Similarly, Figure 16 presents the measured and predicted gaseous Nitrogen cold flow pressure loss data obtained from the formed AMCC panels. Again, the measured pressure loss data presented represents the average of 50 measurements taken for each flow condition. The uncertainty bands for each data point is the estimated measurement uncertainty for the specific test setup. As this figure illustrates the predicted pressure loss approximates the best curve fit of the measure data to within -1.75% to +3.6%.

Comparison of the flat and formed panel configuration data illustrates an important piece of data. The pressure loss through the formed configuration is 4 to 15% higher than the flat configuration test data. This change is partly due to the increased frictional pressure losses due to curvature effects and partly due to changes in the passage width and depth which occur during the forming process. The relative proportions of the changes have been quantified through forming and cold flow experiments and can be predicted.

Subscale Formed Platelet Chamber Testing

The hot fire test data of the Subscale Chamber Formed Platelet Liner provided the opportunity to validate the platelet liner flow passage thermal/hydraulic model. The subscale chamber is cooled with cryogenic hydrogen and operates with oxygen/hydrogen propellants.

Table 1 summarizes the hot fire test conditions of the Subscale Chamber Formed Platelet Liner to date, (December, 1993). As shown, the Subscale Chamber Formed Platelet Liner has been hot fired for a total of 133.1 seconds, with 54 seconds at main stage chamber pressure.

Figure 17 provides a comparison between the measured and predicted coolant pressure loss through the platelet liner. This comparison illustrates that the predicted pressure loss is within -5.4 to +4.3% of the measured data. This is a very favorable comparison. Meanwhile, Figure 18 compares the measured and predicted coolant temperature rise for each test. These data demonstrate that the predicted coolant temperature rise is within ±5.5% of the measured coolant temperature rise.

These test data illustrate that the thermal/hydraulic model currently in place can accurately (within 5.5%) predict coolant flow conditions during hot fire testing.

CONCLUSIONS

The hydraulic predictive capabilities for platelet devices have been demonstrated for various passage designs, panel configurations (i.e. flat and formed), and with both ambient and non-symmetrically heated cryogenic gas flows. This demonstrated thermal/hydraulic predictive tool facilitates the design of future platelet fabricated flow passages.

The fluid pressure loss through a platelet passage includes the effect of a loss mechanism, the land-to-land tie drag, not present in conventional milled slot flow passages. However, the flexibility of platelet fabrication and design (i.e. precisely controlled thin hot gas wall thicknesses and continuous variation in channel width and depth) results in flow pressure losses less than that predicted for passages manufactured with conventional machining practices, while providing higher cooling efficiencies (i.e. lower hot gas wall temperatures for a given coolant flowrate and pressure loss).

ACKNOWLEDGMENTS

Significant contributions to the effort described herein were made by the following:

AEROJET: Wendell Burkhardt, Jackie Cabeal, Charlie Carter, Mickey Fedun, Fred Ferrante, Pat Fuetz, William Hayes, Dave Heimlich, Dave Janke, Tim Meland, Jeanine Miller, Russ Miller, Steve Perry, Tracy Petersen, and Don Rousar

NASA MSFC: Fred Bramm, Dick Counts, and Sandy Elam

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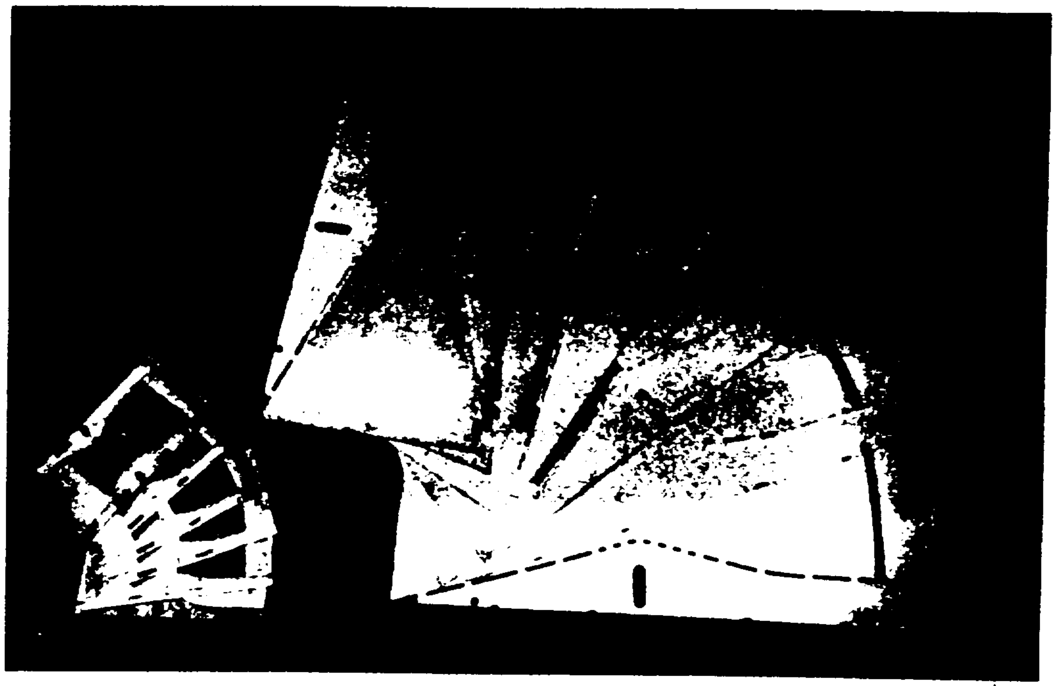
Table 1 Subscale Chamber Formed Platelet Liner Hot Fire Test Results

Test No.	Chamber Pressure (psia)	Mixture Ratio	Coolant Flowrate (lbm/sec)	Measured: Coolant Pressure Loss (psi)	Measured: Coolant Temp. Rise (^{o}F)
005	1141	6.65	11.1	1055	75
008	1308	6.7	11.0	1039	82
014	1750	6.7	10.95	1011	97
015	1767	6.4	11.25	1017	96
017	2150	5.7	11.1	1204	101
018	2323	6.3	11.4	1202	106
019	2480	6.4	11.9	1274	107
020	2524	6.2	11.6	1280	108.5
021	2476	6.3	11.75	1267	108
022	2164	4.7	11.6	1257	92
023	2107	4.5	11.3	1250	90
024	2805	6.3	11.8	1225	117



log 930.827

Figure 1 Platelets for the Subscale Chamber and Advanced Main Combustion Chamber Cooling Liners

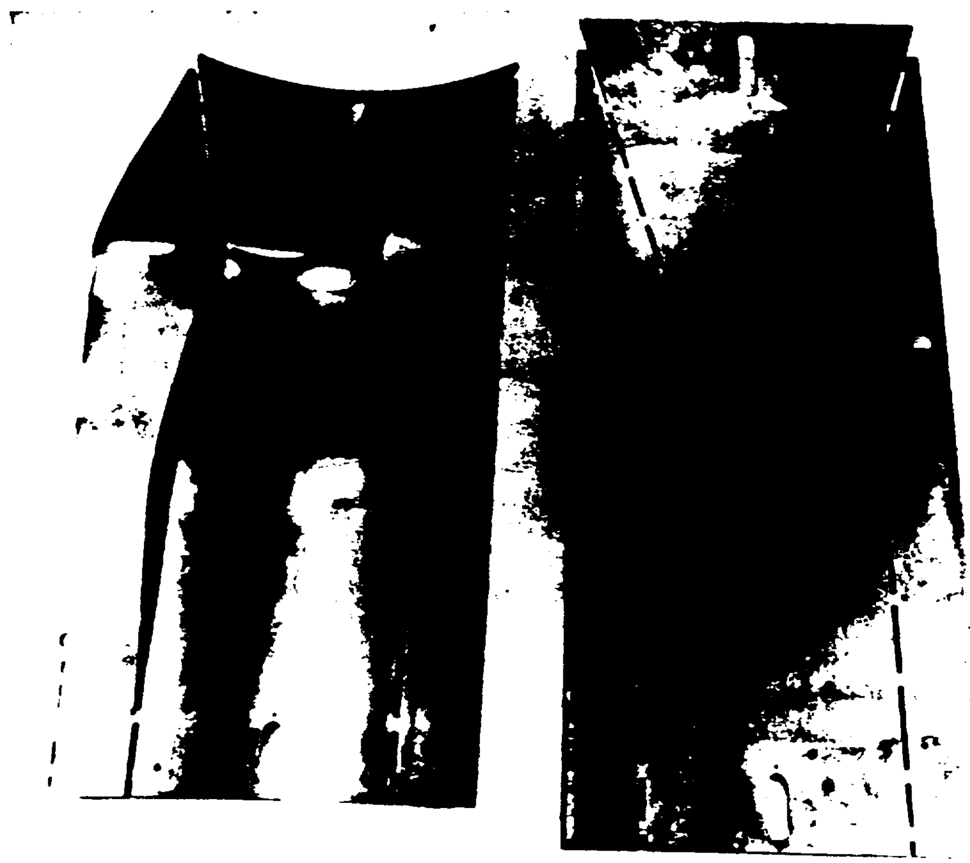
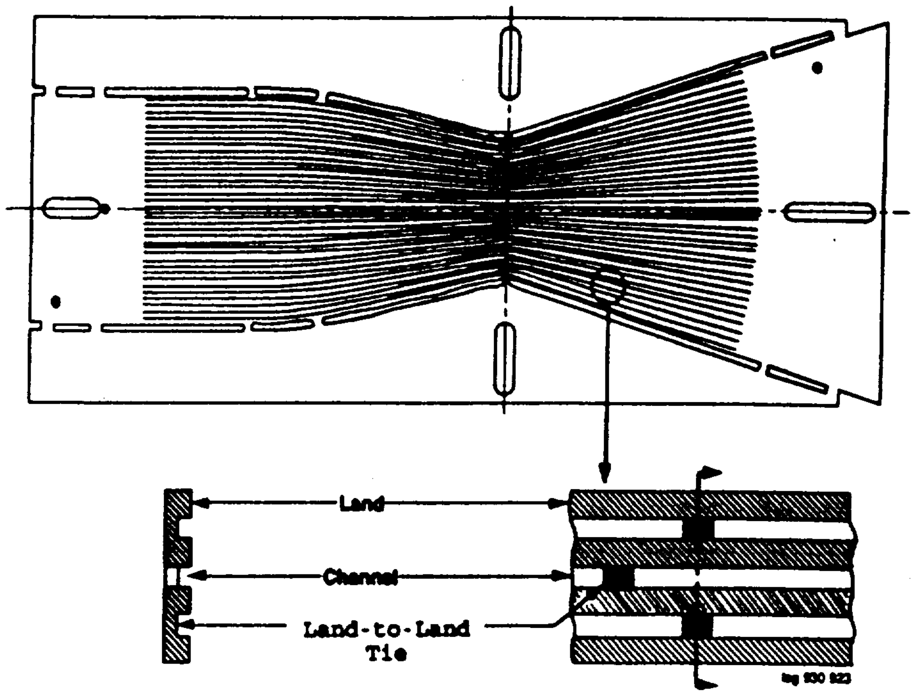
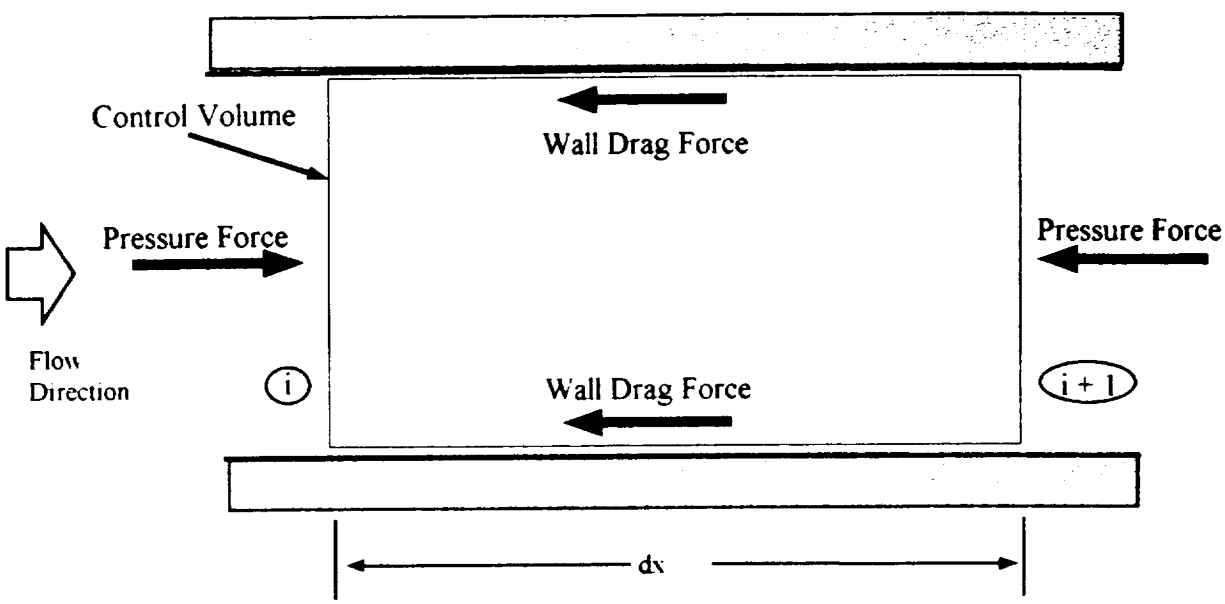


Figure 2 Flat and Formed AMCC Platelet Cooling Liners



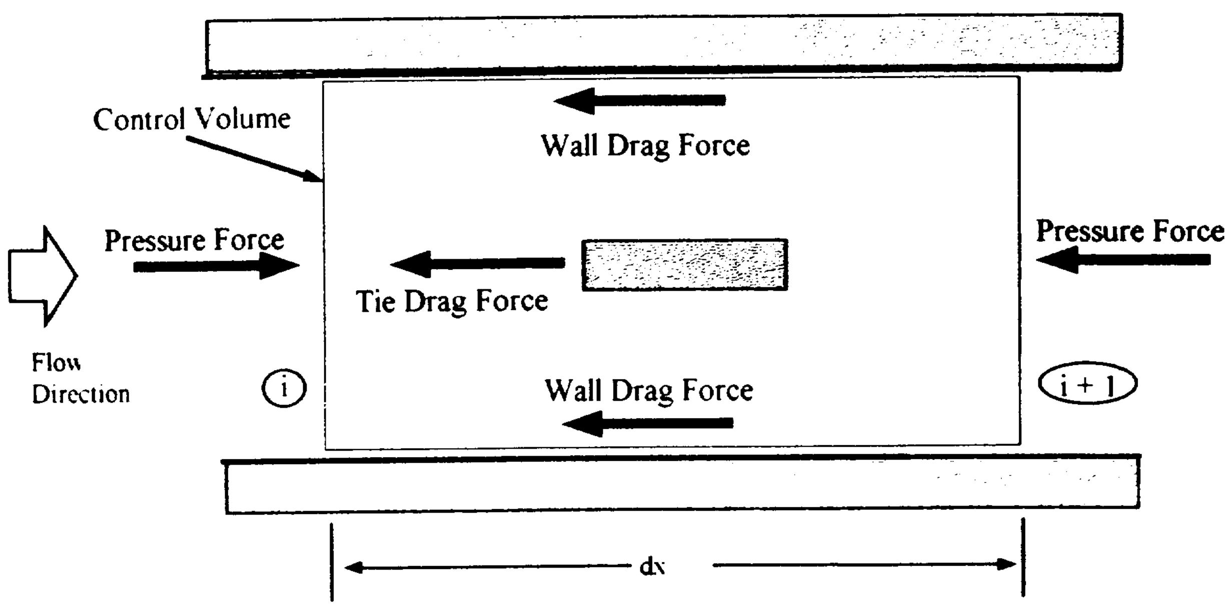
log 930.923

Figure 3 Schematic of Land-to-Land Ties within a Platelet Sheet



$$F_{Pressure} + F_{Wall\ Drag} = \text{Change in Momentum Flux}$$

Figure 4 Flow Passage Pressure Loss Control Volume



$$F_{\text{Pressure}} + F_{\text{Wall Drag}} + F_{\text{Tie Drag}} = \text{Change in Momentum Flux}$$

Figure 5 Flow Passage Pressure Loss Control Volume with Land-to-Land Tie Losses

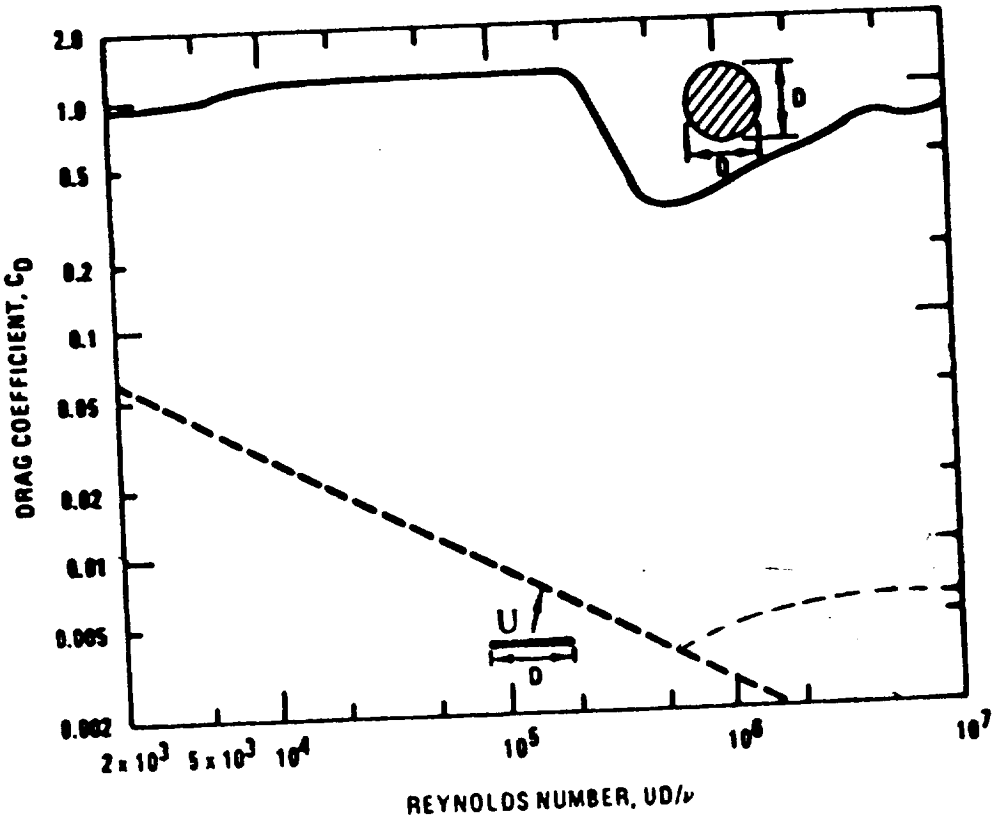
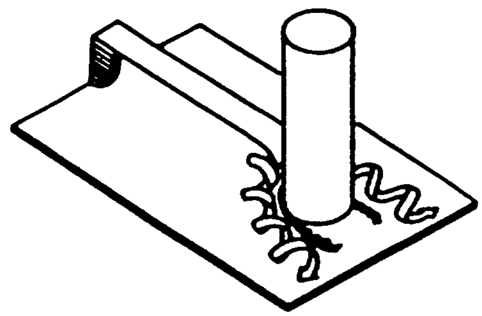


Figure 6 Typical Drag Coefficient Data for Flow Obstructions in Cross Flow



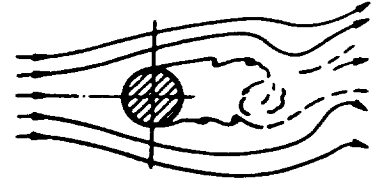
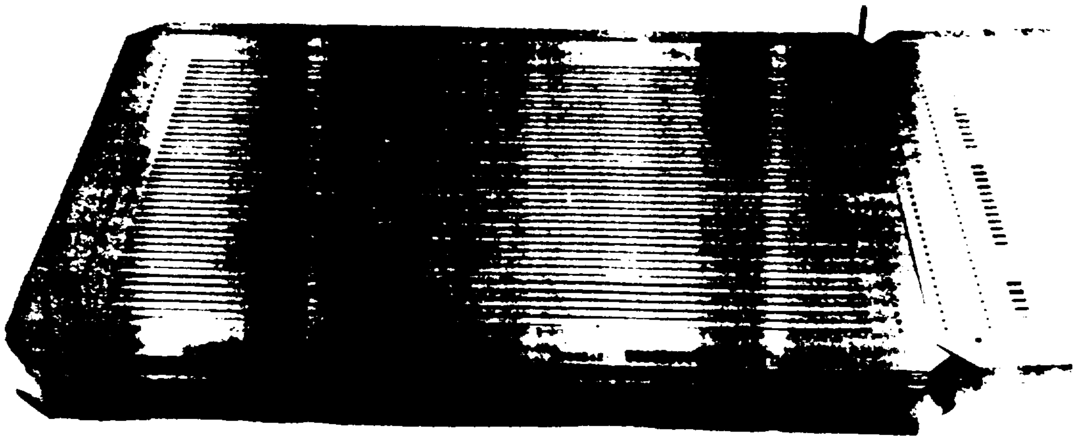
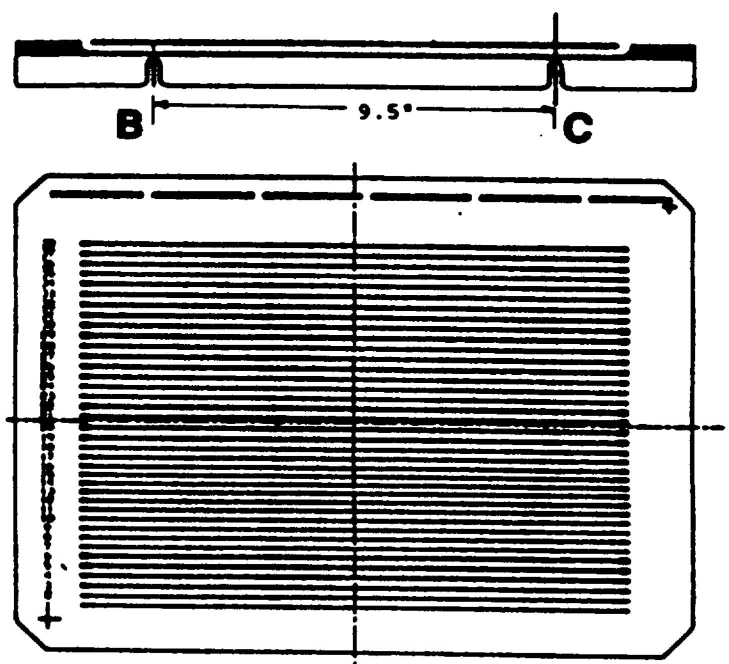


Figure 7 Flow Patterns Induced by a Flow Obstruction in Cross Flow

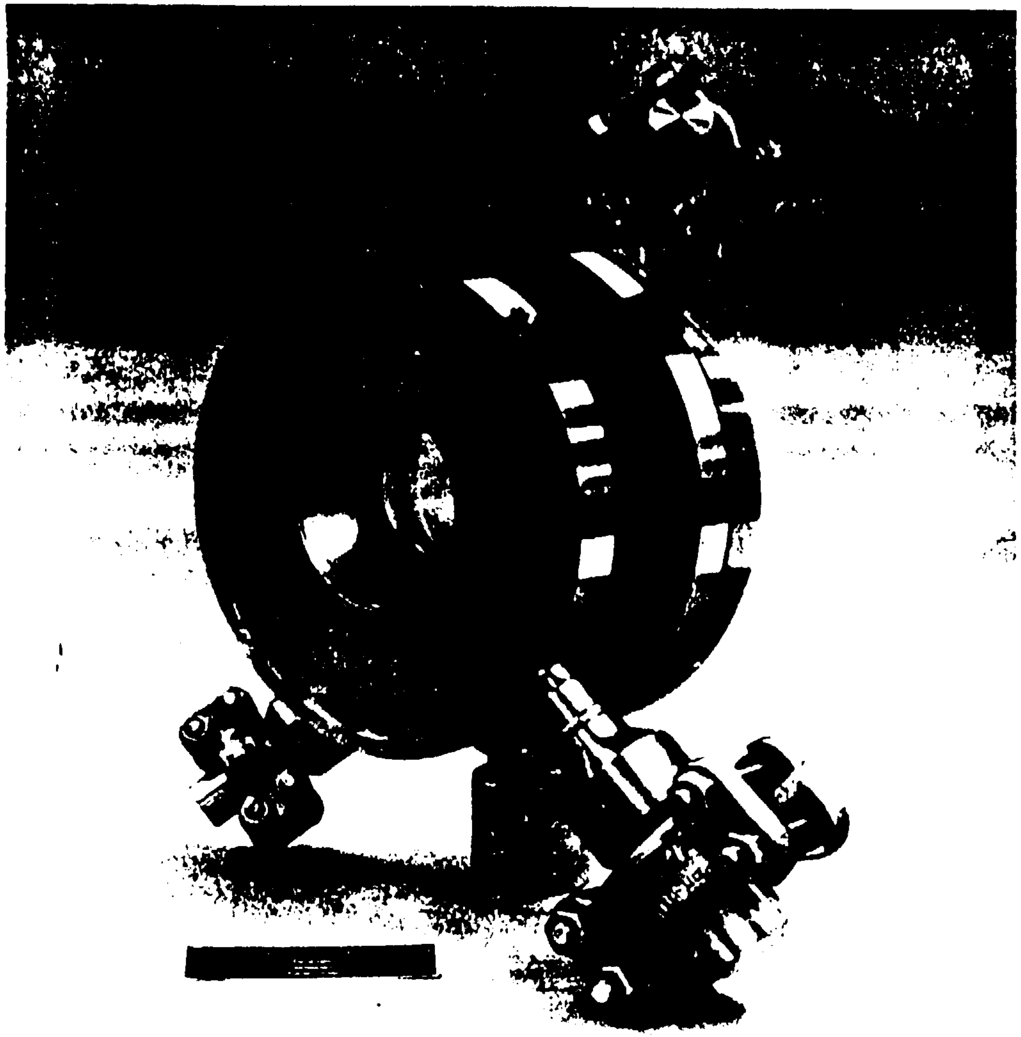


(a)



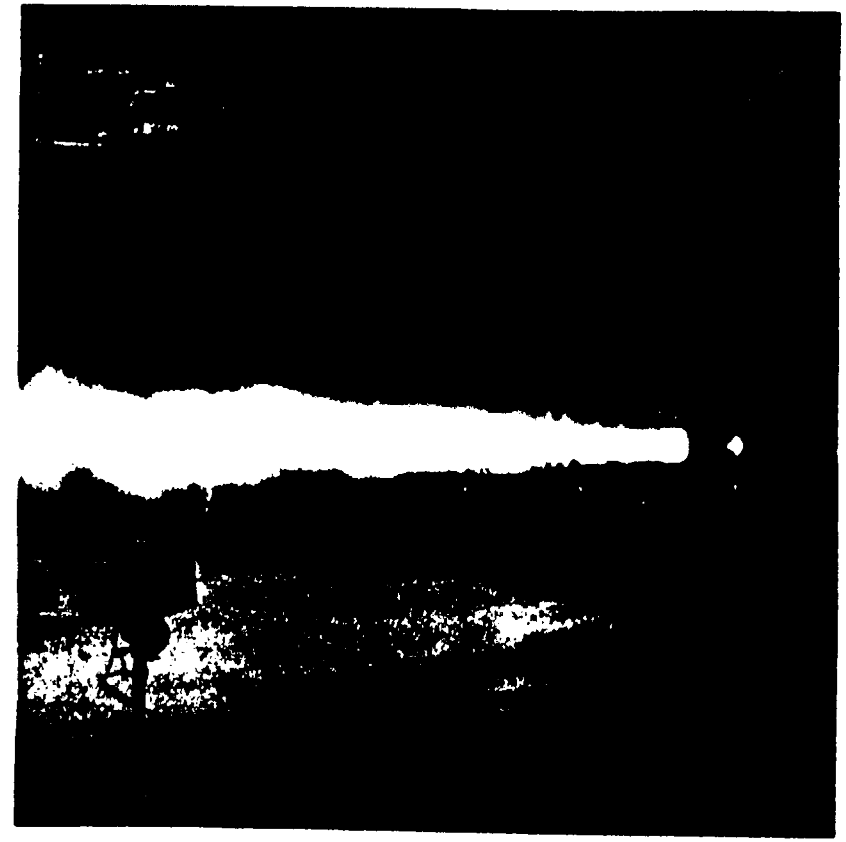
(b)

Figure 8 Hydraulic Characterization Panel, (a) Photograph of a Panel without Close-out Platelets in place, (b) Panels include static pressure ports in each flow passage.



log 930.830

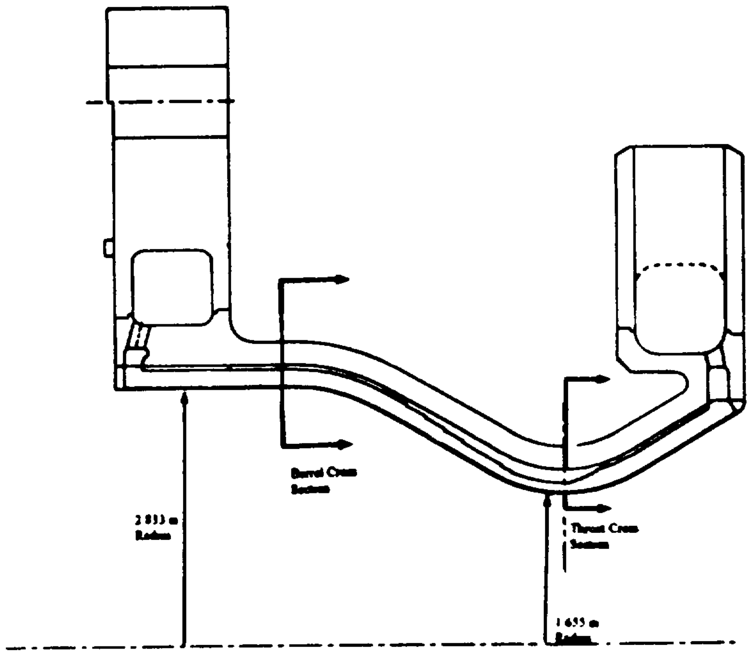
(a)



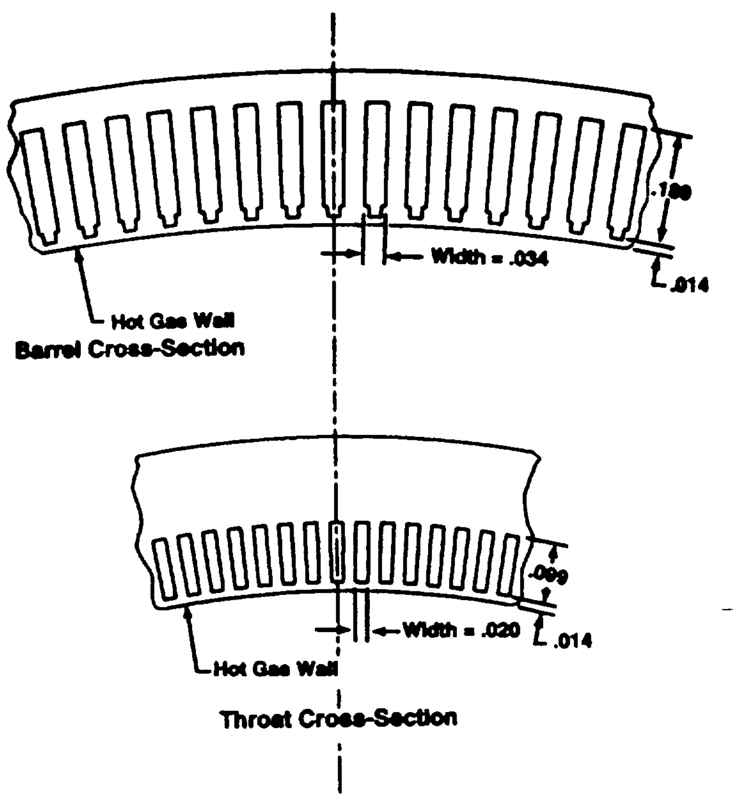
log 930.847

(b)

Figure 9 Subscale Chamber Formed Platelet Liner, (a) Subscale Chamber Assembly, (b) Formed Platelet Technology Demonstrated with Hot Fire Tests.



(a)



(b)

Figure 10 Subscale Chamber Formed Platelet Liner Design Geometry

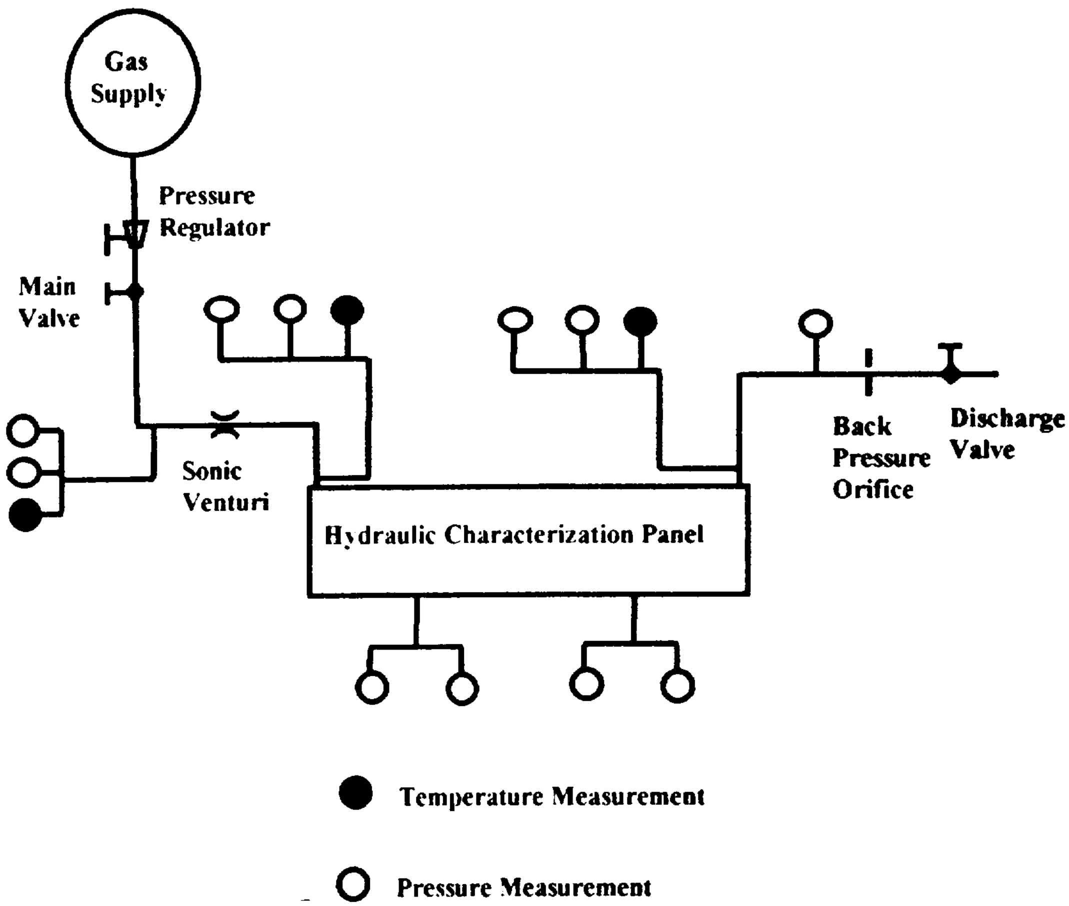


Figure 11 Schematic of the Test Setup for the Gaseous Cold Flows of the Hydraulic Characterization Panels

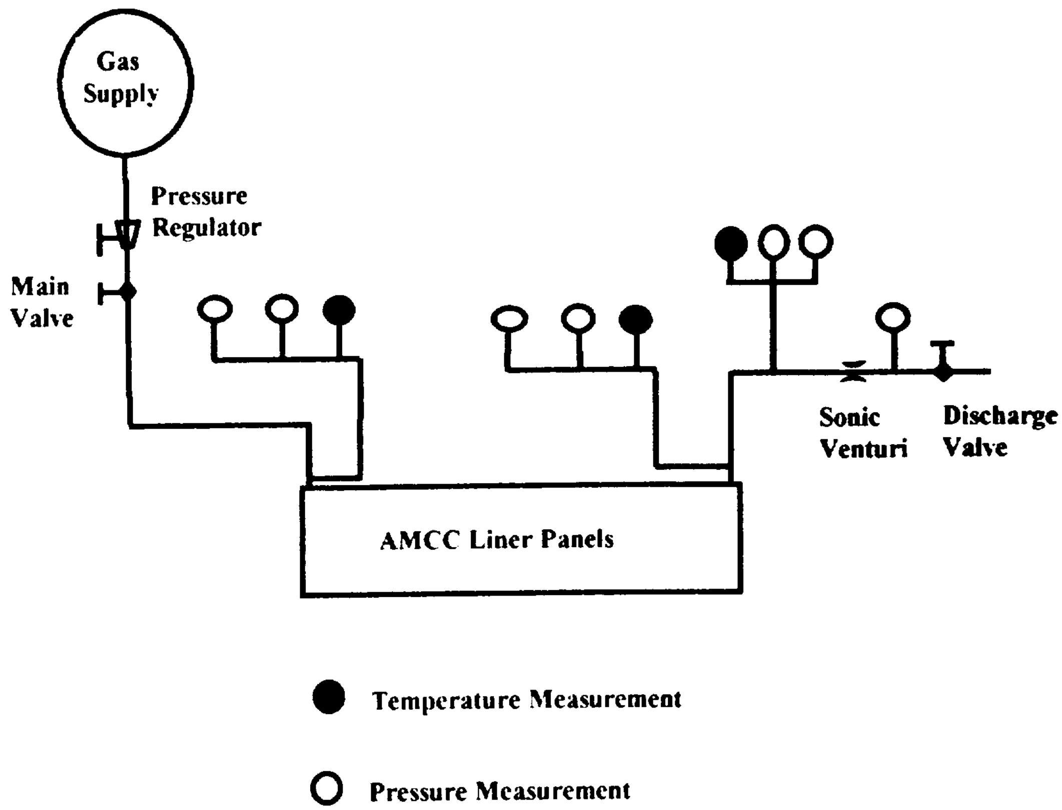


Figure 12 Schematic of AMCC Liner Panels Gaseous Cold Flow Test Setup

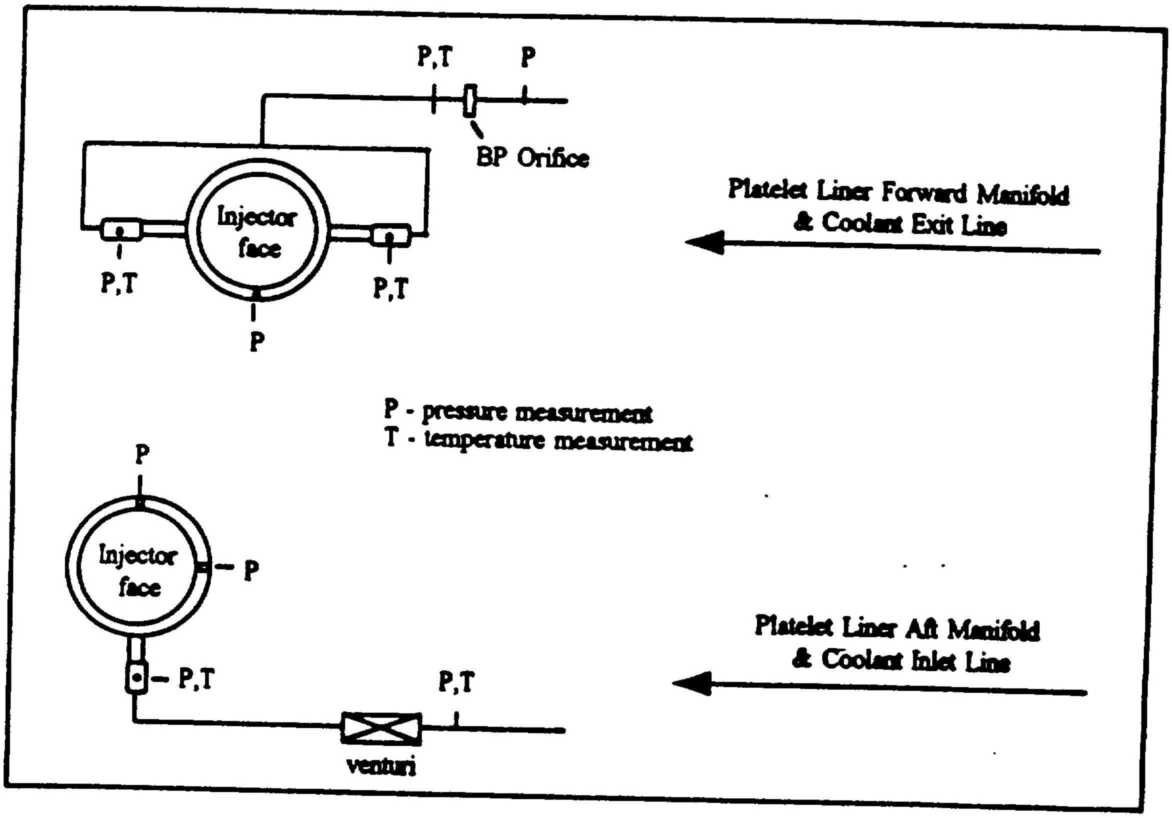


Figure 13 Schematic of the Subscale Chamber Formed Platelet Liner Test Setup

Figure 14 Typical Test Data from the Hydraulic Characterization Panels

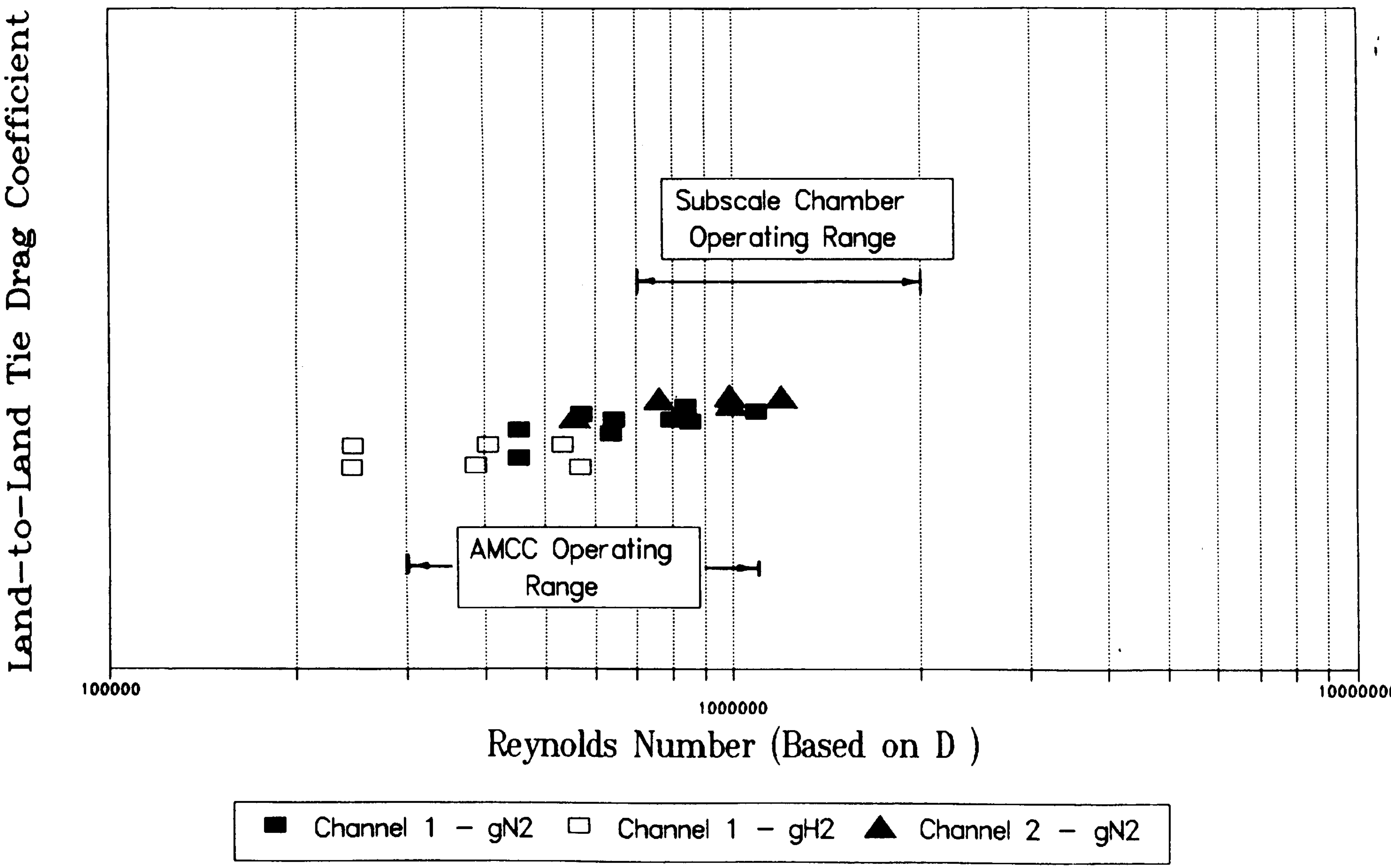


Figure 15 AMCC Flat Panel Configuration Gaseous Nitrogen Cold Flow Test Data

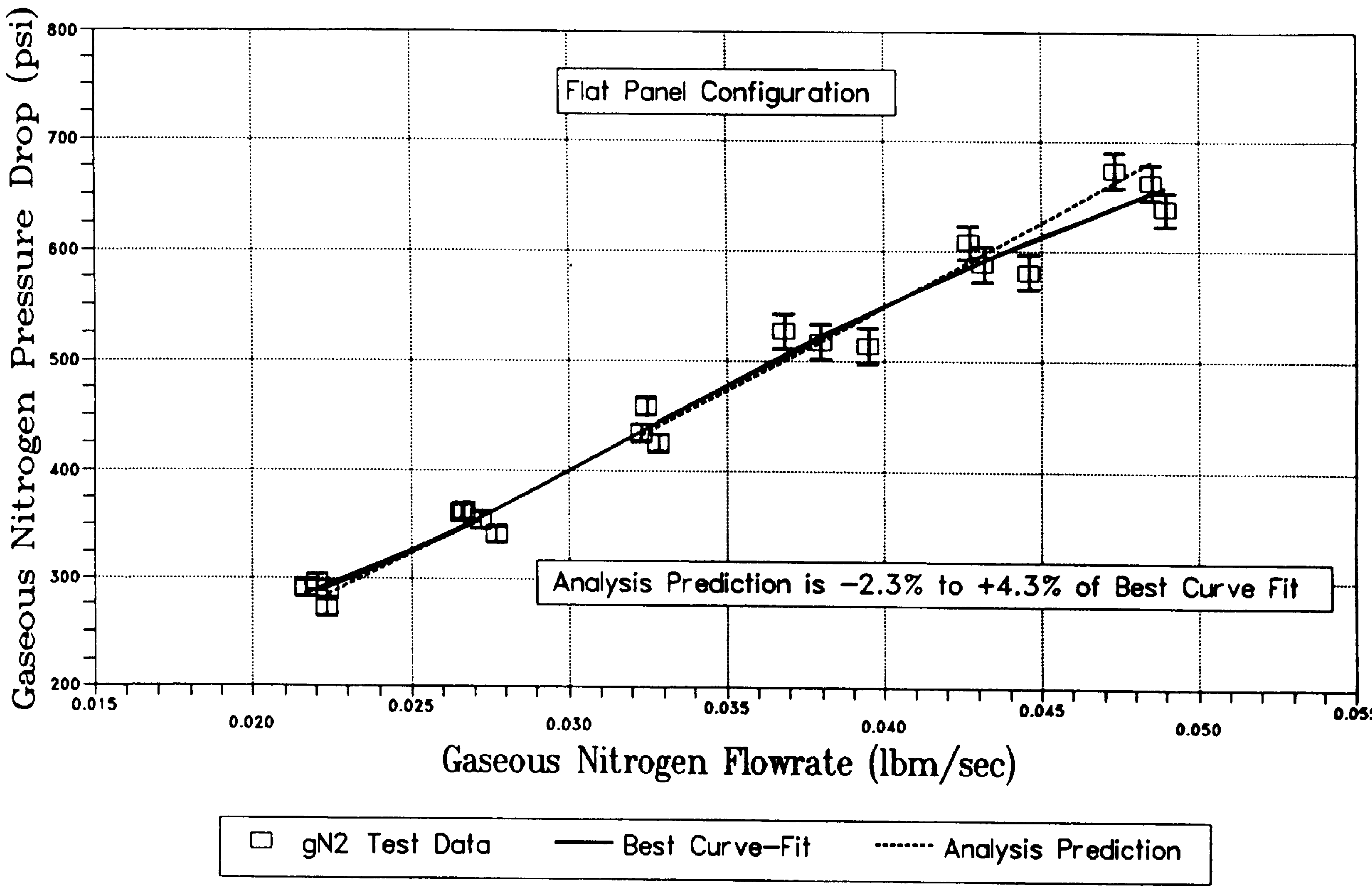
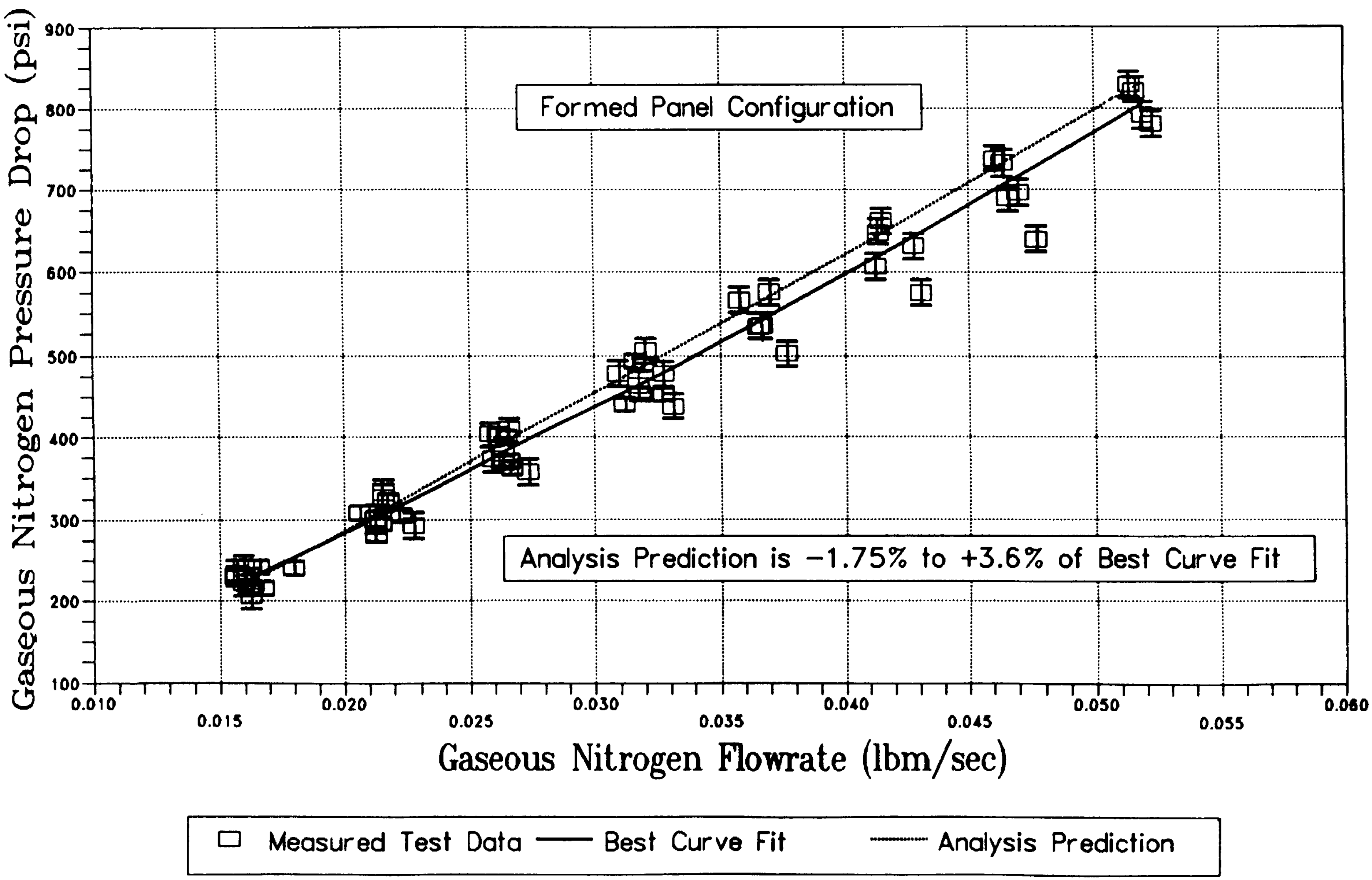


Figure 16 AMCC Formed Panel Configuration Gaseous Nitrogen Cold Flow Test Data



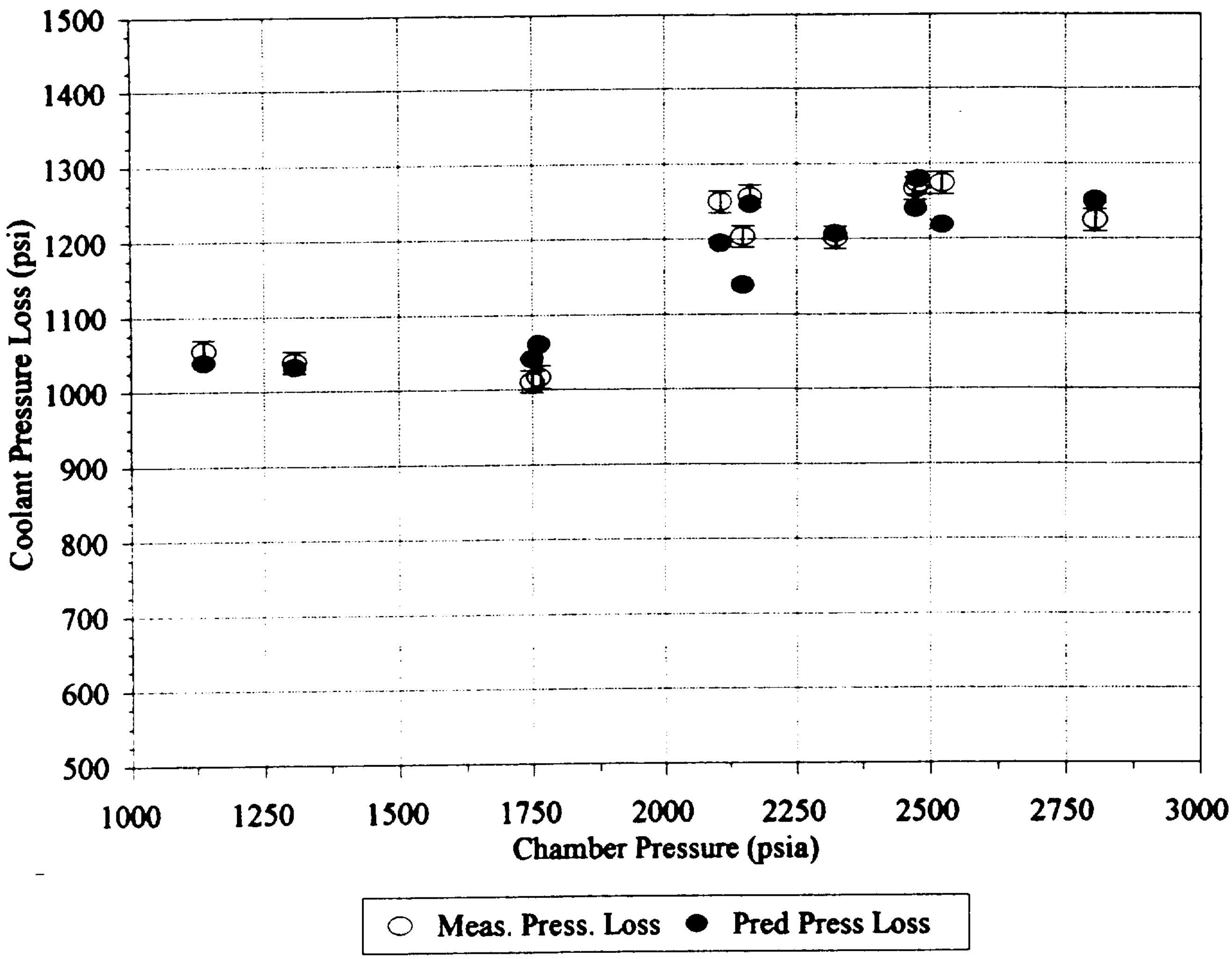


Figure 17 Subscale Chamber Formed Platelet Liner Hot Fire Tests Coolant Pressure Loss Data

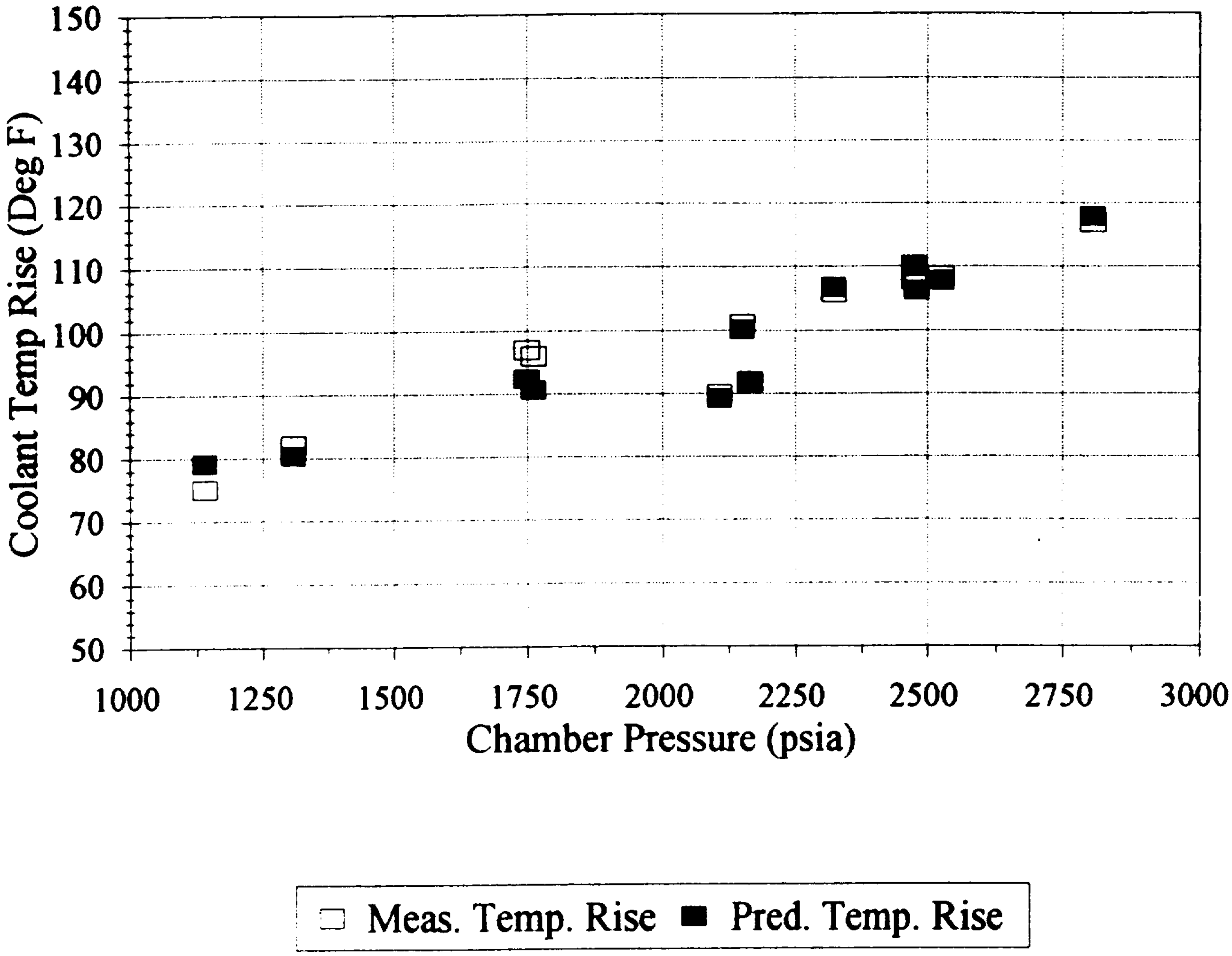


Figure 18 Subscale Chamber Formed Platelet Liner Hot Fire Tests Coolant Temperature Rise Data